Fermilab

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Coalescing

I Current Practice

- proton coalescing
- antiproton coalescing

II Development Paths

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- 2.5 MHz acceleration
- stacking
  - slip
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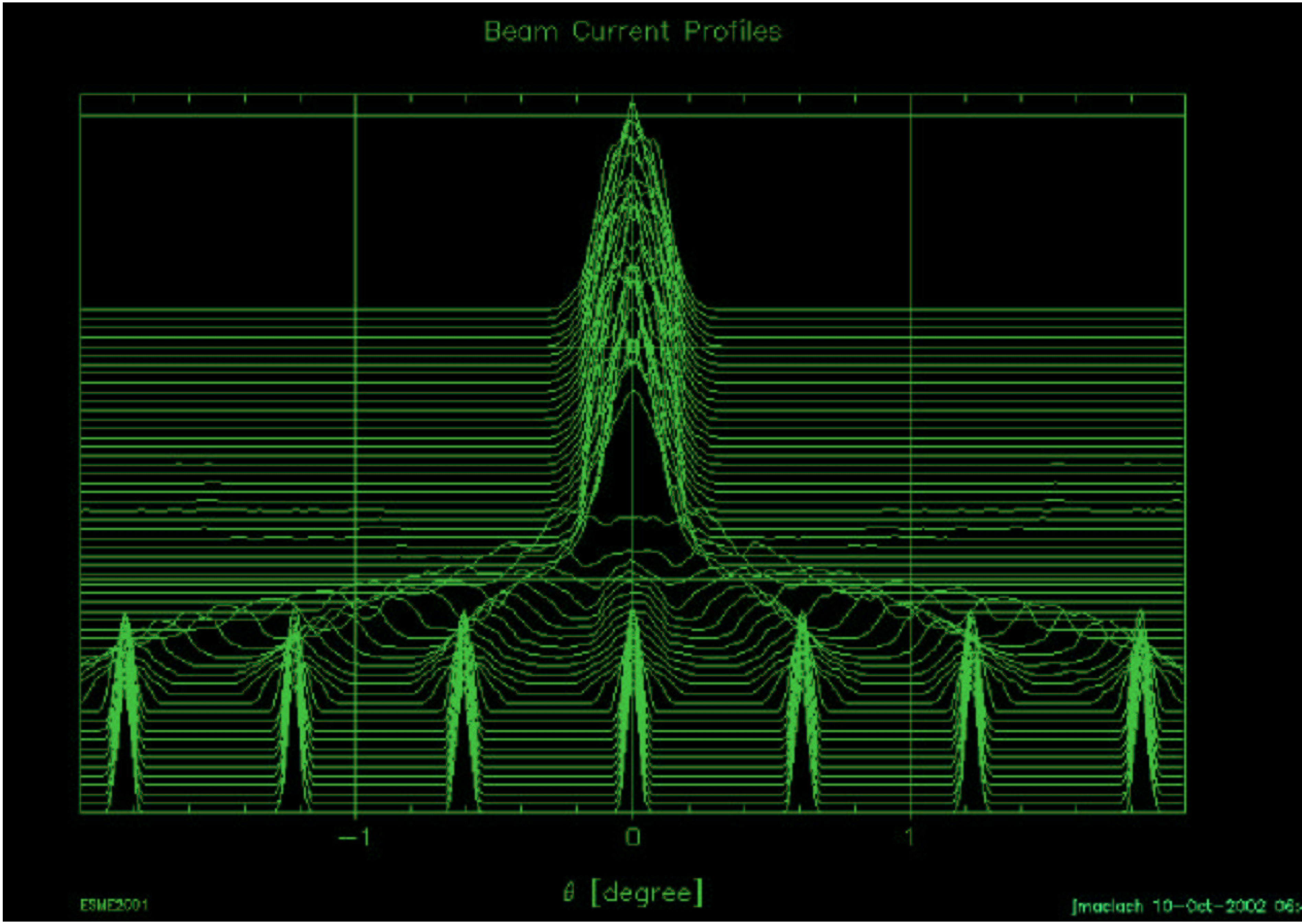
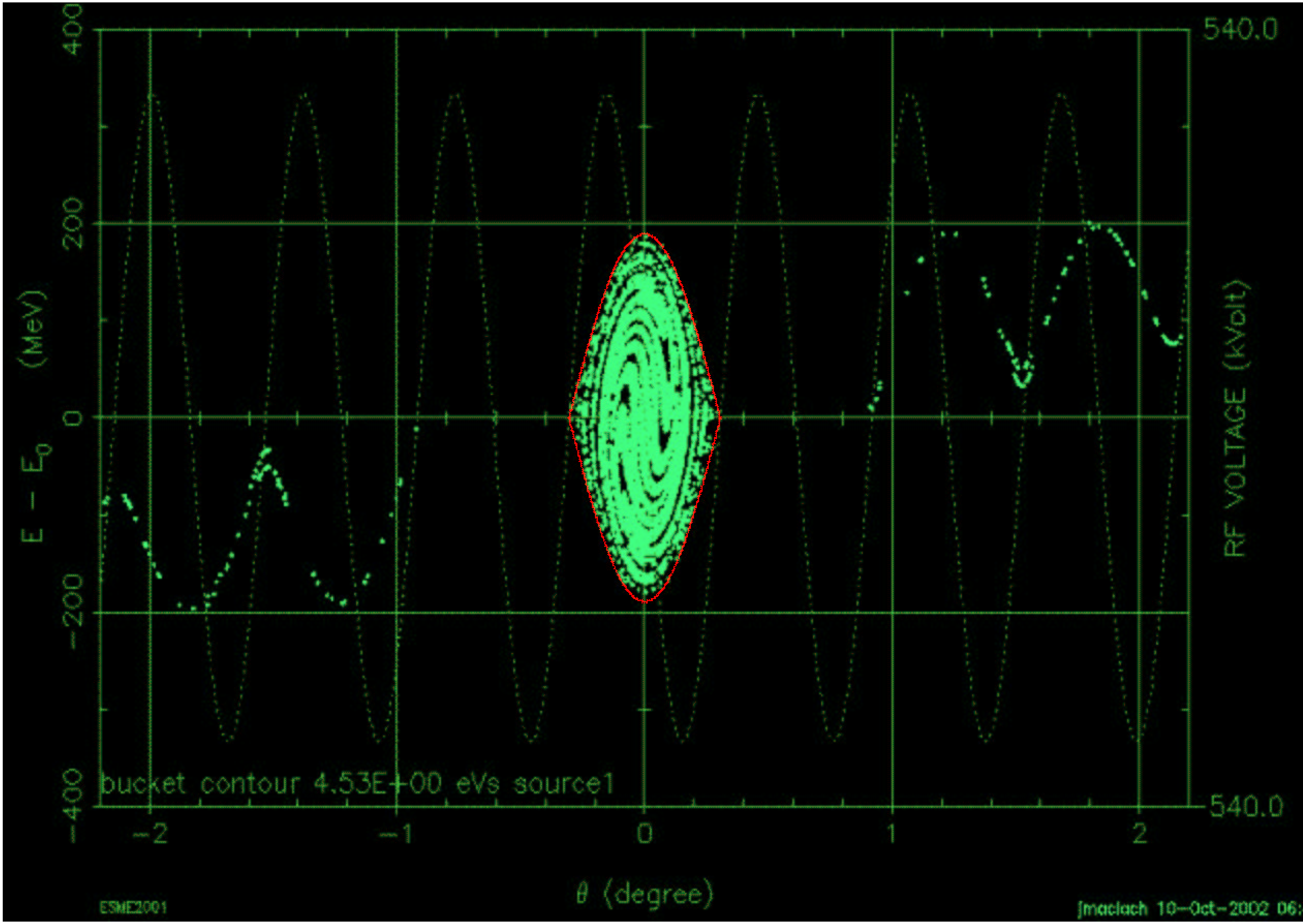
  - moving barrier
- obtaining uniform $\bar{p}$ shots / avoiding $\bar{p}$ coalescing

Proton Coalescing

Bunches in excess of $3 \cdot 10^{11}$ for the Tevatron must be constructed from 5 – 7 Booster bunches of $\sim 6 \cdot 10^{10}$ protons. The resulting bunch is too large to be accelerated through transition with the normal 53 MHz rf, so the coalescing process is carried out at 150 GeV, just before injection into the Tevatron.

The next slide shows a bunchlength mountain range for the coalescing of seven bunches of 0.21 eVs each, about 70 % of the current typical value. The beam charge distribution is plotted at 4.4 ms intervals. Because the capture efficency deteriorates significantly for bunches larger than 0.2 eVs, dilution during transition crossing is important whether or not the coalesced emittance is considered accetable. Proton bunches at injection can be 0.15 eVs or even less. The current practice of intentionally diluting the beam from the Booster to ~ 0.3 eVs is a temporary expedient which will be cut back or eliminated when a MI longitudinal damper becomes available. injection, the growth at transition is an issue, a later subject in this talk. The second figure shows the longitudinal phase space distribution corresponding to the final bunch current trace. The central bucket of 4.53 eVs is practically full with 98 % of the beam and the remainder is mostly uncaptured. The 95 % emittance is 3.6 eVs.


Beam Current Profiles
−1
0
1
θ [degree]
ESME2001
jmaclach 10-Oct-2002 06:



400
200
0
-200
-400
E - E0 (MeV)
540.0
540.0
RF VOLTAGE (kVolt)
-2
-1
0
1
2
θ (degree)
bucket contour 4.53E+00 eVs source1
ESME2001
jmaclach 10-Oct-2002 06:

The proton coalescing cycle for seven 0.27 eVs bunches totalling $3.3 \cdot 10^{11}$ has been followed with the effect of fundamental beam loading of the 53 MHz cavities and space charge taken into account. Differing assumptions on the effectiveness of the beam loading compensation yield a range of results between 60 % and 24 % for the dilution of the trailing bunch. Unless the beam loading is well compensated, it is necessary to shift the phase of the 53 MHz for capture of the coalesced bunch. Typically, the rotated ensemble is shifted by half of a 53 MHz bucket during the rotation. Even with perfect beam loading compensation, the dilution at transition from the space charge focusing discontinuity remains a limitation on emittance preservation in coalescing. The possibility of improving the details of the match at transition deserves more attention.

Table 1: The minimum and maximum rms emittance of 7 proton bunches of 0.27 eVs initial bunch area through the MI 2B cycle are given in the first and second line respectively for each energy entry. The coalescing is not included in these results. The five cases differ only in the amount of attenuation of the fundamental beam loading in the 53 MHz cavities.

Beam Energy	Beam Loading Compensation				
	none	20 dB	26 dB	40 dB	full
8.9	0.0530	0.0530	0.0530	0.0530	0.0537
	0.0530	0.0530	0.0530	0.0530	0.0537
20.5	0.0534	0.0535	0.0535	0.0535	0.0539
	0.0532	0.0531	0.0532	0.0532	0.0539
25.0	0.0601	0.0569	0.0566	0.0557	0.0562
	0.0559	0.0551	0.0551	0.0552	0.0562
85.0	0.0854	0.0731	0.0723	0.0688	0.0666
	0.0714	0.0642	0.0642	0.0642	0.0666
115.0	0.0852	0.0732	0.0721	0.0687	0.0666
	0.0712	0.0642	0.0641	0.0642	0.0666
140.0	0.0848	0.0730	0.0719	0.0688	0.0665
	0.0710	0.0642	0.0642	0.0642	0.0665
150.0	0.0844	0.0730	0.0719	0.0685	0.0665
	0.0710	0.0642	0.0642	0.0641	0.0665

Now that the Booster longitudinal damper is working satisfactorily, the effective emittance available at injection is considerably improved. However, instability in the MI (presumably coupled bunch) requires the emittance to be diluted in the Booster by anti-damping. The reported injected emittance now in use for the proton bunches for coalescing is 0.3 eVs. For the work reported below, 0.27 eVs was used. If the emittance is really this large, the coalescing efficiency might benefit from an increase in the 53 MHz snap (low) voltage above 35 kV.

There may be an under-reporting of coalesced emittances. The SBD determines an rms bunch length using a relation between the first and third fourier amplitudes that applies to a Gaussian distribution. The bunch shapes are manifestly not Gaussian. The ratio between the bounding emittance and the rms emittance for an elliptical distribution is 5.05. An elliptical distribution is fairly representative of well behaved bunches. Some of our bunches look almost like the projection of a uniform distribution for which the boundary to rms ratio is 3.86. When I determine a bunch area from an rms emittance I use the factor 5.05. As I understand, for the procedure used by I. Kourbanis the corresponding factor is four. Comparing rms bunch widths may seem to evade the issue. Howerver, the comparison then needs to be made at the same energy and rf amplitude where the results are practically guaranteed to be simillar because the same modeling machinery is being used.

A residual 53 MHz voltage of amplitude somewhere between 5 kV and 1 kV and uncertain phase is present during the 2.5 MHz rotation. It results from a combination of beam loading and imperfect counter-phasing of the accelerating cavities. The counterphasing can be tuned to reduce both problems but beam loading can only be compensated on average in this manner. If it could be eliminated completely, the current technique would work better. The efficiency goes up to 99 % and the 95 % emittance drops to 3.2 eVs. However in this situation the procedure would be modified. An adiabatic coalescing yielding bunches of < 2 eVs could be used.

The combined effect of lower losses and lower longitudinal emittance consequent to effective elimination of the residual 53 MHz voltage could raise luminosity ~ 30 % or more (educated guess).

Antiproton Coalescing

Coalescing for antiprotons differs from that for protons in at least the following:

1. four 53 MHz bunch trains seperated by 396 ns, produced from four 2.5 MHz bunches

2. bunch trains from 7 to 13 or so bunches each, depending on which shot

3. bunch 2.5 MHz emittances from 0.5 to 1.5 eVs, depending on which shot

4. intensity down by a factor of three or more

5. 53 MHz emittance from $\sim$ 0.2 eVs at central bunch to much less at end of train

Table 2 (following) gives the coalescing efficiency and final emittance for initial 2.5 MHz emittance from 0.5 eVs to 1.3 eVs and residual 53 MHz voltage from 100 V to 5 kV. The parameters are those in current use; they represent a compromise to achieve the best net result for the full range of initial conditions.

Table 2: The antiproton coalescing efficency [%] and final emittance [eVs] for three different initial emittances (0.5, 0.9, and 1.3 eVs) under conditions of residual 53 MHz voltage from 100 V to 5 kV with instances at both 180° and -90° phase.

V_{resid}	$\varepsilon_{init} = 0.5$		$\varepsilon_{init} = 0.9$		$\varepsilon_{init} = 1.3$	
	eff.	ε_{final}	eff.	ε_{final}	eff.	ε_{final}
0.1 (180°)	100	1.72	99.4	2.21	98.8	3.18
1.0 (180°)	100	1.69	99.2	2.31	98.7	3.15
1.0 (-90°)	93.1	~ 4.2	79.2	~ 4.2	65.2	~ 4.2
2.5 (180°)	100	1.91	99.1	2.73	98.5	3.38
2.5 (-90°)	92.6	~ 4.2	78.2	~ 4.2	65.0	~ 4.2
5.0 (180°)	99.3	3.12	96.5	3.99	95.9	4.16

The phase of the residual voltage will be 180° if the counter-phase angle is correct but the voltages of the counter-phased cavity groups are unequal; a quadrature phase can come either from an error in the counter-phasing or beam loading. In practice, the counter phasing is tuned empirically so that it will be roughly correct for the average of whatever beam loading voltage remains after the beam loading compensation feedback. However, from the Table 2 it appears that typical coalescing efficiencies, *viz.* 95 % – 70 %, imply a residual quadrature voltage $\sim$ 1 kV.

Table 3: The population-weighted average rms emittance of 9 antiproton bunches through the MI 2A cycle is given in the first line of each energy entry. The second line of each entry is the rms emittance of the central bunch. The 53 MHz voltage pre and post snap is 450 kV, the snap voltage is 30 kV, and the 2.5 MHz rotation voltage is 60 kV for the three sets of results. A beam loading voltage of 800 V constant over all of the bunches was included. Results are given for initial 2.5 MHz bunch areas of 0.5, 0.9, and 1.5 eVs.

Energy	$\varepsilon_{2.5} = 0.5$	$\varepsilon_{2.5} = 0.9$	$\varepsilon_{2.5} = 1.5$
8.9	0.0241	0.0308	0.0351
	0.0267	0.0344	0.0452
25.0	0.0243	0.0313	0.0362
	0.0271	0.0356	0.0455
85.0	0.0254	0.0336	0.0387
	0.0281	0.0387	0.0490
115.0	0.0254	0.0338	0.0394
	0.0283	0.0388	0.0516
140.0	0.0254	0.0338	0.0394
	0.0283	0.0389	0.0513
150.0	0.0255	0.0340	0.0393
	0.0283	0.0391	0.0512
Coalesced . . .			
. . . ε_{rms}	0.352	0.507	0.691
. . . $\varepsilon_{95\%}$	1.91	2.52	3.96
. . . blow up	2.0	2.0	2.1
. . . efficiency	100 %	99.5 %	96.2 %

Transition Crossing

The emittance growth of small bunches passing through transition in the MI is typically about 30 %, where “small” is < 0.25 eVs. Because the coalescing efficiency is strongly dependent on the 53 MHz emittances, it is useful to look for practical means of improvement. A small reduction in bunch area should be quite helpful for coalescing. Work has started recently to take the results from the longitudinal envelope equation (Sørenssen & Hereward, Courant) and the nonlinear single-particle equations (Jie Wei) as guidence in MI-specific numerical modeling. Early results relate only to the non-linear chromatic effects, *i. e.*, without beam charge. These results are relevent to the antiproton bunches; the resulting parameter curves give < 10 % bunch growth. It is intended to develop a more detailed model for making estimates of expected dilution.

This is a new work-in-progress. The principal point in mentioning it at this stage is to put it on the agenda and to recommend non-zero priority. The object is to look in the short term for optimized curves and to consider for somewhat longer term low-cost expedients (like an inductive insert, for example — an old, old idea).

2.5 MHz $\overline{\text{p}}$ Acceleration

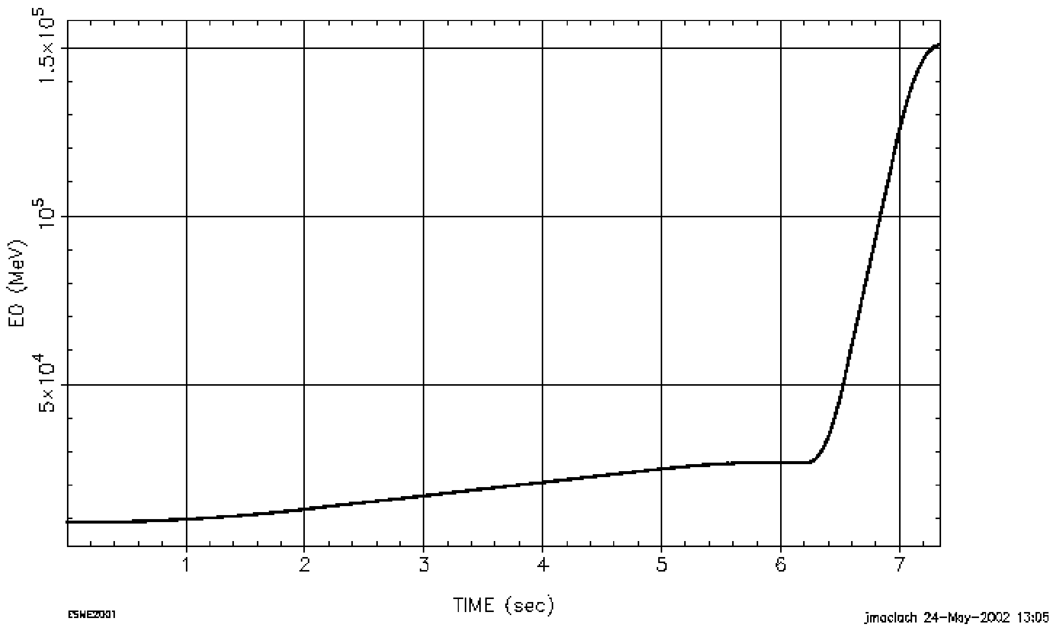
Antiproton bunches of 1.5 eVs are required for the Tevatron but can not be accelerated through transition in the Main Injector (MI) with the h=588 rf system. Coalescing is the present solution, but several schemes have been considered for bypassing that process because of its emittance dilution and particle loss. The MI has 60 kV of 2.5 MHz available for coalescing. It has been proposed by several people over the years to accelerate past transition at h=28 and carry on with the h=588. Chandra Bhat has developed parameters for h=28 acceleration from 8 GeV followed by h=588 acceleration above transition (MI-0260 & MI-0260rev); MacLachlan has recently revisited and slightly revised them (TM-2177).

It is practicable to accelerate the 1.5 eVs $\bar{p}$ bunches in about seven seconds with no loss and less than ten percent emittance growth using the existing 2.5 MHz cavities. The 2.5 MHz cavities were designed to be powered for only a short time, but tests (Dey, Bhat, *et al.*) have shown that it is practicable to use them for several seconds.

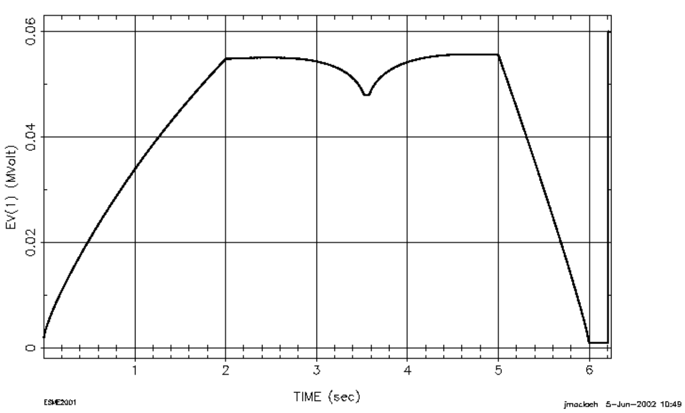
The ramp curve is shown in the first plot. The first parabola ends at 12 GeV followed by a linear segment to 24 GeV and a parabola onto a front porch at 26 GeV where the handoff to h=588 occurs. The $\dot{p}$ and the rf voltage and phase are kept constant on the linear ramp for $\pm$25 ms around the time of transition crossing, *i. e.*, a little more than the nonadiabatic time

$$T_{\mathrm{na}} = \pm \left[\frac{\beta_T^2 \gamma_T^4}{4\pi f_{\mathrm{rf}}} \frac{|\tan\phi_{\mathrm{s}}|}{\dot{\gamma}^2} \right]^{1/3} \quad ,$$

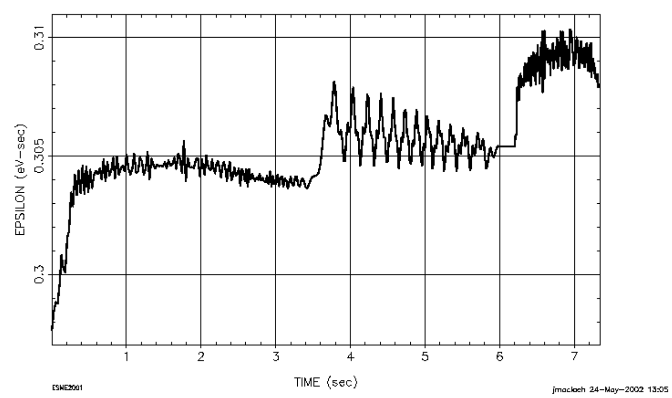
where the symbols are defined and parameter values assigned in Table 4. The motion on the decreasing parabola is not quite adiabatic; the bunch arrives with a considerable tilt. It is rotated to minimum height at low voltage after the h=56 linearizing voltage is turned on; then the h=28 and h=56 voltages are jumped to the maximum 60 kV and 10 kV respectively for a quarter period rotation to minimum width. A matching 3 eVs h=588 bucket (700 kV) is turned on suddenly at time of minimum bunch width. Because the bunch is large, the h=588 portion of the ramp is held to 160 GeV/s maximum.



Ramp (energy *vs*. time) for a full $\bar{p}$ cycle with h=28 acceleration to 26 GeV



h=28 voltage (8 – 26 GeV)



Emittance in h=28 acceleration to 26 GeV

Table 4: Main Injector rf parameters for h=28 $\bar{p}$ acceleration. Energy dependent parameters are evaluated at transition energy.

R_{eq}	mean orbit radius	528.57	m
γ_{T}	transition gamma	21.8	
E_{inj}	injection energy	8.93827	GeV
E_{max}	top energy	150.93827	GeV
E_{T}	transition energy	20.4543	GeV
β_{T}	Lorentz β at transition	0.99895	
$\dot{\gamma}$	maximum rate of change of γ	$\hookleftarrow$	
$\hookrightarrow$	below 26 GeV	4.263	s^{-1}
$\hookrightarrow$	26 – 150 GeV	170.526	s^{-1}
ϕ_{s}	synchronous phase	67.48	deg
f_{rf}	accelerating frequency	2.52449	MHz
$\widehat{V}_{28}$	maximum 2.5 MHz voltage	60	kV
$\widehat{V}_{56}$	maximum 5 MHz voltage (rotation)	10	kV
$\widehat{V}_{588}$	maximum 53 MHz voltage	4	MV
$\tilde{\varepsilon}_{\mathrm{initial}}$	initial rms emittance of bunch	0.298	eVs
$\tilde{\varepsilon}_{\mathrm{final}}$	final rms emittance of bunch	0.308	eVs
$\varepsilon_{\mathrm{initial}}$	initial area of 95 % of bunch	1.31	eVs
$\varepsilon_{\mathrm{final}}$	final area of 95 % of bunch	$\hookleftarrow$	
$\hookrightarrow$	(beam charge ignored)	1.44	eVs
$\hookrightarrow$	($Z_{\parallel}$ model included)	1.42	eVs
	total cycle time	7.345	s

Summary and results

The initial 95 % area of the 1.5 eVs bunch is 1.31 eVs, and its rms emittance is 0.298 eVs; an elliptical distribution is assumed. At 150 GeV, the emittances have grown to 1.44 (+9.9 %) and 0.308 eVs (+3.4 %) respectively. The time development of the rms emittance shown in the third figure indicates growth after transition and after the switch to h=588 acceleration. In both cases the growth is the result of unavoidable shape mismatch. The 95 % emittance grows by a larger factor because it more strongly reflects the development of a tenuous tail to the distribution by filamentation arising from the small mismatches. These are very promising results; both technical matters and complications in principle arising from the beam current will make it practically impossible to actually match them. Nonetheless, the peak current is reasonable and the complications are generally understood.